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Component Sharing in the Management of Product Variety: A Study of Automotive Braking Systems

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Product variety in many industries has increased steadily throughout this century. Component sharing—using the same version of a component across multiple products—is increasingly viewed by companies as a way to offer high variety in the marketplace while retaining low variety in their operations. Yet, despite the popularity of component sharing in industry, little is known about how to design an effective component-sharing strategy or about the factors that influence the success of such a strategy. In this paper we critically examine component sharing using automotive front brakes as an example. We consider three basic questions: (1) What are the key drivers and trade-offs of component-sharing decisions? (2) How much variation exists in actual component-sharing practice? and (3) How can this variation be explained? To answer these questions, we develop an analytic model of component sharing and show through empirical testing that this model explains much of the variation in sharing practice for automotive braking systems. We find that the optimal number of brake rotors is a function of the range of vehicle weights, sales volume, fixed component design and tooling costs, variable costs, and the variation in production volume across the models of the product line. We conclude with a discussion of the general managerial implications of our findings.

(Component Sharing; Product Variety; Commonality; Product Platform; Product Design)

1. Introduction

Product variety can be defined on two dimensions: the breadth of products that a firm offers at a given time and the rate at which the firm replaces existing products with new products. Both dimensions of variety have steadily increased in many industries (Pine 1992, Sanderson and Uzumeri 1995, Fisher et al. 1996), so that the managerial challenge now is how to provide the high degree of variety that seems necessary for competitive success while retaining the scale economies required for low cost (Lancaster 1990).

The approaches companies have taken in coping

with this challenge can be classified as *process based* or *product based*. Process-based strategies seek to imbue production and distribution processes with sufficient flexibility to enable them to accommodate a high level of variety at reasonable cost. Product-based strategies seek product designs that allow high variety in the marketplace while presenting the production and distribution system with a relatively low level of component variety and assembly complexity.

Component sharing is a product-based strategy that depends on the fact that families of similar products have similar components. For example, all cars have a

steering wheel, tires, an engine, a windshield, etc. In principle, an auto company offering 100 car models could have 100 distinct steering wheel designs, one for each model. A more logical approach may be to have a smaller number of steering wheel designs, with each design shared over a set of models. The key issue in such a component sharing approach is, given a product portfolio, how many versions of each type of component should exist, and what subset of products should use each component design?

Companies increasingly view component sharing as a way to have high variety in the marketplace and low variety in their operations. In the 1980s, Black & Decker rationalized its product lines by clustering its products by motor sizes. By eliminating unnecessary proliferation, the number of motor sizes was reduced fivefold, despite an increase in the number of end products (Meyer and Lehnerd 1997). Similarly, Dell Computers assembles several different end products using a relatively small set of core components (Dell 1994).

Despite the popularity of component sharing in industry, very little is known about how to design an effective component sharing strategy or about the factors that influence the success of such a strategy. Ulrich (1995) has examined the relationship between product architecture and component sharing. Rutenberg (1969) examined a product line design problem in which products for different customer segments have different minimum specifications, and a given product can be used in any segment for which it meets the minimum specifications. In a multiyear study examining the factors contributing to the performance of auto development projects, Clark and Fujimoto (1991) reported that the fraction of carry-over components and the fraction of components designed by suppliers are both negatively related to development time and to engineering hours. These factors differ significantly across regions: Japanese firms use more new components, but also delegate much of the development work to suppliers, leading to a lower scope overall. Gupta and Krishnan (1996) developed a technique for creating assembly sequences that yield common intermediate subassemblies. Whitney (1988) and Nevins and Whitney (1987) have documented some of the

component sharing practices in current use. Suzue and Kohdate (1990) and Galsworth (1994) provide some heuristic approaches to reducing parts complexity for assembled goods.

In this paper we critically examine component sharing using automotive front brakes as an example. We consider three basic questions: (1) What are the key drivers and trade-offs of component sharing decisions? (2) How much variation exists in actual component sharing practice? and (3) How can this variation be explained?

Our approach to the research questions is both analytical and empirical. We first identify the key costs related to component sharing and develop an optimization model, for a particular class of problem, to predict what we would expect to be ideal component sharing practice. We then use the results of this optimization model to formulate testable hypotheses about industrial practice. Finally, using data from the auto industry over 11 years, we test these hypotheses. Although we focus on automotive front braking systems, our intention is to provide generalizable insights applicable in other industries, and we discuss at the end of the paper how we believe our results apply to other industries.

The remainder of this paper is organized as follows. In the next section, we identify the key drivers of component sharing decisions. In §3, we discuss our choice of domain, front braking systems, and present the optimization model. In §4, we formally pose our hypotheses and report on the empirical study of brakes sharing in the auto industry. In §5 we provide concluding remarks.

2. Key Drivers of Component Sharing

The decision to share a component is linked to issues of cost, product quality and performance, and organizational structure. In this section, we highlight these key issues and the relevant factors that support or inhibit component sharing.

The cost issues may be usefully thought of as the investment requirements for new products; the variable costs of production; and the system costs of production, distribution, and after-sale support.

Investment in new products includes the costs of product development and the fixed costs of production. Because each new and unique component must be designed and tested, component sharing can reduce the cost of product development. Each new and unique component generally also requires an investment in tooling or other fixed costs of production. Therefore component sharing may also reduce the required production investment associated with a new product.

Component sharing involves factors that may both increase and decrease the variable costs of production. Because a shared component will be produced in higher volumes than components used in only a single type of product, economies of scale in the production process may lead to lower unit variable costs. However, a shared component must be designed to perform adequately in the most stringent product application in which it will be used. Often the most stringent performance requirements are substantially greater than those for the least stringent application in which the component will be used. This excess capability may incur a unit variable cost penalty relative to the variable costs of unique components designed for each unique product application.

In addition to investment costs and variable costs of production, firms incur "system costs" of production, distribution, and after-sale support. Examples of activities associated with such costs are quality assurance, procurement, and spare-parts inventory. These costs are driven in large measure by the number of unique parts present in the production and distribution system (Ulrich et al. 1993, Banker 1990). As a result, component sharing may lead to reduced system costs.

Component sharing influences product quality and performance in two countervailing ways. The quality and performance of a shared component may be higher than that of components designed and produced for unique applications. This enhanced quality and performance may arise because of the learning and quality improvement associated with increased volume, and because increased production volume may justify higher levels of investment in component development and refinement. Component sharing

may also improve performance on average because a shared component must be designed to meet the performance requirements for the most stringent product application in which it will be used, and these requirements are often substantially greater than those for the least stringent application.

On the other hand, some elements of product performance may suffer when components are shared. Performance degradation is especially likely relative to the holistic attributes of product performance (Ulrich 1995, Ulrich and Ellison 1998). By holistic performance attributes we mean those attributes that arise from all or most of the physical elements of a product.

Component sharing is also linked to the structure of the product development organization. Current trends are toward project organizations and "heavy-weight project teams" (Wheelwright and Clark 1992). The goal of these organizations is to foster responsiveness and speed by granting autonomy and control. The consequence of this autonomy may be more difficult coordination with other activities within the firm. Platform products (i.e., products sharing a substantial set of components) are frequently developed by the same team. In such settings, component sharing within platforms may be facilitated, but sharing across platforms may be inhibited. Functional organizations, in contrast, may be less responsive and nimble, but they may foster greater coordination among projects and therefore easier sharing of components.

Categorizing Components for the Purposes of Component Sharing

We find it useful to divide components into two categories: (a) components with a strong influence on product quality, and (b) components with a weak influence on product quality. While these categories are very coarse, discussions with managers and engineers at Toyota, Ford, and General Motors indicate that similar categorizations are common in practice, and we believe that a simple framework helps focus the research issues.¹ Here we provide a short

¹ For example, at Toyota, components are classified along a continuum from "design" to "function" (Yasukawa 1992). A "component" fully at the design pole is exterior paint. For such components, the maximum variety (i.e., minimum sharing) is desired. A component

discussion of each category; a more detailed treatment of these issues is provided in Robertson and Ulrich (1998) and Ulrich and Ellison (1998).

A. Components with a Strong Influence on Product Quality. For these components, the influence on product quality may take several forms. (By “product quality” we intend overall customer perception of product performance, not just “conformance” quality.) First, a component may have a direct, nearly linear impact on the customer’s perception of product quality. For example, improvements or degradations to the quality of an automotive audio system could lead directly to corresponding changes in the perceived quality of the overall product. Second, a component may relate to overall product quality in a complex, nonlinear fashion. For example, an automobile fender contributes to, among other characteristics, the aesthetics of an automobile. However, this relationship is not direct and it would be impossible to define a quality index for fenders in the same way as one could for audio systems. Third, a component may have an indirect influence on product quality because of its size, mass, or other incidental properties. For example, using a battery with excess capacity may not have a direct influence on the perceived quality of the electrical performance of the automobile, but it will degrade the acceleration, fuel economy, and braking performance of the car, because the battery will be heavier than necessary.

B. Components with a Weak Influence on Product Quality. The attributes of these components relate only weakly or not at all to overall product quality. There are at least two reasons such components can exist. First, some components implement a simple function which if performed to a certain level will result in acceptable quality, but which if performed better will not increase the perceived quality of the overall product. Components in this category include relatively minor “jelly bean” parts, including lamp bulbs for tail lights, turn signals, etc.; fasteners of various types; and electrical connectors. Customers do

fully at the function pole is a bolt. For these components, the maximum sharing is desired.

not care about these components unless their performance falls below a threshold.² Second, some components are part of a more complex subsystem of the product that benefits from substantial “slack” in its design. By this we mean that an arbitrary choice of one component can be accommodated at little or no cost by adjustments to the parameters of some other component. For example, a timing circuit containing a resistor and a capacitor may be implemented with an only approximately correct value of the capacitor in conjunction with a resistor tuned precisely to achieve the desired performance.

While many of the insights in the paper relate to both categories of components, our primary focus is Category B—components with a weak influence on product quality. For these components, the cost issues in component sharing are prominent. Interestingly, in certain cases, components from Category A can be treated as if they are from Category B—when the quality penalty of using the “wrong” component can be easily modeled as a variable cost. In focusing on Category B, we remain aware that the other category is important. We return to these categories when we interpret and discuss the results of the analytical and empirical research.

3. Optimization of Component Sharing: The Example of Automotive Front Brakes

A car’s rate of deceleration, for a given vehicle mass, is determined by the restraining force that can be applied by the tires to the road. To a first approximation, the maximum value of this deceleration (in g ’s) is equal to the coefficient of friction of the tires, assuming that the braking system can apply enough torque to lock the wheels.³ Given the desired deceleration (gen-

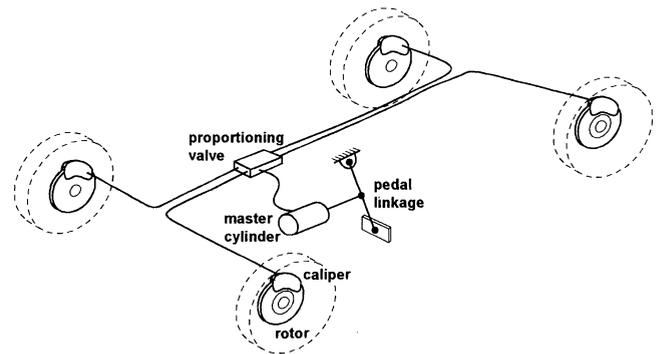
² This threshold phenomenon is similar to the “must be” type of quality attributes in the *Kano* methodology (Shiba et al. 1993).

³ This is because deceleration is given by braking force divided by mass; and maximum braking force is given by mass times coefficient of friction. However, the mechanics of braking are complicated by three factors: (1) load distribution on the front and rear wheels depends on the height of the center of mass of the vehicle, (2) the coefficient of friction between the tire and the road is nonlinear

erally derived from the desired stopping distance from 100 kph), tires are selected to have the required coefficient of friction.⁴ Then the braking system is designed to achieve the stopping potential of the tires by exerting enough torque on the wheels to bring the car to the brink of skidding.

Figure 1 depicts a typical braking system. The force exerted by the driver on the brake pedal is transmitted by the pedal linkage to the master cylinder and then via brake fluid through the brake lines to calipers (containing slave cylinders and brake pads), at each wheel which press brake shoes against a rotor or a drum,⁵ generating friction and a deceleration torque on the wheels. The torque on the wheels relative to the force on the pedal is determined by the mechanical advantage of the pedal linkage (and of boosters if the car is equipped with power brakes), the ratio of the area of the master cylinder to those of the slave cylinders, and the radius of the rotors. A brake designer must choose these parameters so that an acceptable force on the brake pedal produces the required torque on the wheels. Several other factors constrain the design of a brake. The size of components must not exceed the space available for them. For example, increasing the length of the pedal arm increases the mechanical advantage of the pedal linkage and is an inexpensive way to multiply foot pressure. But as the pedal arm grows in length it eventually will not fit in the available space. Similarly, the dimensions of the master cylinder, calipers, and rotors are all constrained by the geometry of the car. Usually rotors and their corresponding calipers are proportionate in size, so picking a rotor size largely determines caliper size. Finally, friction between the calipers and the rotors generates heat at a rate proportional to braking torque and the speed of the vehicle. If rotors have insufficient mass and/or surface area, they can overheat, causing

Figure 1 Schematic Illustration of Components of an Automotive Braking System (Booster System Not Shown)



degradation of braking performance, a phenomenon called *fade*.

The fact that several independent parameters collectively determine braking torque facilitates sharing because it allows a designer to borrow some components from another product and design the remaining components to deliver the required torque given the characteristics of the borrowed components. For example, a common strategy is to borrow the booster and the master cylinder from another car and design a unique pedal linkage, rotor, and caliper to complement these components so as to deliver the required torque.

Brake rotors are to some extent "Category A" components, as described in the previous section, but can be easily treated as "Category B" components. Brake rotors exert no direct influence on product quality as long as they are big enough to provide adequate stopping torque and to absorb braking energy. The quality penalty for using a brake rotor that is larger than necessary is excess weight, which can lead to poor acceleration, fuel economy, and stopping distance performance. However, in automobile design, weight and cost are equivalents. Components with excess weight can be thought of as "costing" more because their excess "cost" can be "spent" on other components in the vehicle to reduce weight. (From discussions with automobile industry experts, we learned that for most automobiles, the shadow price of weight is about \$5 of unit manufacturing cost per kilogram.) By including the cost of excess weight in the analysis, many of the quality issues associated

(decreasing with increasing normal force), and (3) the dynamic coefficient of friction (friction when skidding) is lower than the static coefficient of friction (friction when the wheel is rolling).

⁴ The reason that all tires do not have the maximum possible coefficient of friction is that there is generally a trade-off between coefficient of friction and tread life.

⁵ For simplicity, we will hereafter assume a disk brake system.

with sharing braking components can be treated as cost issues.

Modeling Objectives and Strategy

Several types of models are used in research in the area of design and manufacturing. These models range in mathematical complexity from a simple list of hypothetical variables to equations that attempt to capture most relevant variables and the functional form of the relationship among them. Models are used variously to generate insight, to inform empirical studies, and/or to provide decision support.

In related work (Ramdas 1995), we present a general model of the decisions related to sharing of brake components. This model is a mathematical model aimed at providing decision support. The model takes as inputs a set of cars for which brakes must be designed and a set of possible design alternatives for various types of components (e.g., pedal linkage, booster, master cylinder, calipers, and rotors), and determines which versions of each component should be built and which cars should use each component version to minimize cost subject to constraints on torque and heat dissipation. The cost structure can accommodate both fixed and variable costs of design, production, and logistics. The model can also incorporate compatibility constraints that prohibit use of a particular component with a particular car or another component, based on the geometry of the car and components or on any other considerations. We develop a solution algorithm based on Lagrangian relaxation, which we demonstrate is capable of solving problems of realistic complexity.

For this paper, we present a model for the purpose of gaining insight and for informing our empirical investigation. This model is not intended to capture every nuance of the component sharing problem, but rather is an attempt to generate insights beyond the basic qualitative insights offered in §2. We complement this model with additional numerical exploration and a review of some existing research in product development in order to formulate testable hypotheses for the empirical study described beginning with §4.

General Formulation

We consider the case of the design of front brakes under the assumption that caliper size is proportional to rotor size and hence the only design parameter is rotor size. This simple model will partially illustrate the structure of the more general case and will show how the degree of sharing depends on basic parameters such as fixed and variable costs, the range of vehicle weights in the product line, and sales volume.

The essential features of the problem are as follows. We require front brake rotors for N cars indexed by $j = 1, \dots, N$. A rotor is feasible for a car if it has the capacity to generate torque and dissipate heat as required to meet the stopping distance specification for the car. The larger the size of a rotor, the greater the torque and heat dissipation capacity. All rotors are disks of uniform thickness so the size of a rotor is determined by its diameter. Define

d_j = the diameter of the smallest rotor that satisfies the torque and heat dissipation requirements for car j ,

V_j = predicted sales volume of model j over its remaining life,

$c_j(V)$ = total design, production, and logistics cost of producing volume V of a rotor with diameter d_j . We assume $c_j(V)$ is concave.

Our problem is to determine which of the N possible rotor diameters d_1, \dots, d_N should be introduced and which of the introduced rotors each car should use so as to minimize total cost. (Without loss of generality, we preclude the possibility of a rotor with diameter different from $d_j, j = 1, \dots, N$. Because cost will be greater for a larger diameter rotor, such a possibility would only be economical if a rotor already exists with a diameter different from any $d_j, j = 1, \dots, N$. In actual practice, we could easily accommodate carry-over rotors by including them on the list of available rotors. But, for the purpose of developing insight, there is nothing to be gained by arbitrarily introducing a set of existing rotors.) We assume the cars are indexed so that if $i < j$, then $d_i < d_j$ which means that a rotor with diameter d_j can be used on all cars $i \leq j$.

The concave cost functions allow us to model most reasonable cost structures, such as fixed and variable costs, and nonlinear production economies of scale,

which arise frequently in practice. For example, inventory related costs might be expected to vary with \sqrt{V} . The following optimality property will permit us to represent this problem as a shortest path problem.

PROPOSITION. *There is an optimal solution in which each car j uses the smallest introduced rotor with diameter not less than d_j .*

PROOF. See Appendix.

Rutenberg (1969) noted that problems with this property can be solved by finding the shortest path from vertex 0 to vertex N in a graph with vertex set $\{0, 1, \dots, N\}$ and arcs (i, j) for all $i < j$ of length $c_j(V_{i+1} + \dots + V_j)$. If arc (i, j) appears in the shortest path, then rotor j should be introduced.

Although we can accommodate general, concave cost functions, a common representation of cost in practice is $c_j(V) = c_j^F + c_j^V V$ where c_j^F and c_j^V are fixed and variable costs. The fixed cost c_j^F would typically include the cost of design and tooling. Design cost can be estimated from the engineering hours expected to be spent on designing the rotor. The fixed tooling cost depends on the type of process used to make the rotor, sand casting being the usual choice. Design and tooling costs may vary for different rotors. For example, if an existing rotor is reused, the design cost is zero or an "alteration" cost. The unit production cost c_j^V is comprised of the cost of materials and the cost of machining. For example, the material cost for a cast iron rotor is equal to the weight of the rotor multiplied by the cost of gray cast iron. Since the surface of the rotor needs to be machined, the machining cost for a rotor made by the sand casting process can be calculated as a function of the surface area of the rotor and the unit cost of machining. The "cost" of weight can also be included in the variable cost, c_j^V , in order to model the influence of a particular rotor choice on product quality.

Special Case

To develop intuition on how the optimal number of front rotors varies with model parameters, we focus first on a special case in which d_j is directly proportional to the weight w_j of car j , i.e., $d_j = K'w_j$; car weights are evenly distributed between $W_{\min} = w_1$ and $W_{\max} = w_N$; and cost is comprised of a fixed and

variable cost with variable cost directly proportional to the diameter of the rotor, i.e., $c_j(V) = c^F + c_j^V V$ for all j , where $c_j^V = Kw_j$. These assumptions are reasonable in that bigger cars require bigger rotors, and bigger rotors incur greater variable production cost.

Let N_B denote the number of rotors introduced. We assume that N is large so that N_B can be analyzed as a continuous variable in which case the diameters of the rotors should be evenly distributed with the i th rotor having diameter

$$K' \left[W_{\min} + \frac{i}{N_B} (W_{\max} - W_{\min}) \right]$$

and used on all cars whose weights fall in the interval

$$\left[W_{\min} + \frac{i-1}{N_B} (W_{\max} - W_{\min}), \right. \\ \left. W_{\min} + \frac{i}{N_B} (W_{\max} - W_{\min}) \right]. \quad (1)$$

Let $V = V_1 + \dots + V_N$. Then the total cost $C(N_B)$ of offering N_B rotors is given by

$$C(N_B) = c^F N_B + \sum_{i=1}^{N_B} \left[KW_{\min} + \frac{iK}{N_B} (W_{\max} - W_{\min}) \right] \frac{V}{N_B}. \quad (2)$$

Taking the derivative of $C(N_B)$ with respect to N_B and setting it to zero, we have:

$$N_B^* = \sqrt{K \frac{(W_{\max} - W_{\min})V}{2c^F}} \quad (3)$$

where N_B^* denotes the optimal number of rotors to offer.⁶

⁶ This model assumes that there are no "coordination costs" associated with sharing rotors. This is consistent with the information gleaned from our interviews with automotive design experts. However, one could imagine a situation for a more complex component in which sharing a component incurs coordination costs beyond those incurred by simply designing a unique component for each application. Equation (2) can be easily modified to include coordination costs. If we add a term $\frac{C^c N}{N_B}$ to capture coordination costs which increase in the amount of sharing, then the expression for the optimal number of brakes will include the addition of the term $2C^c N$ in the numerator.

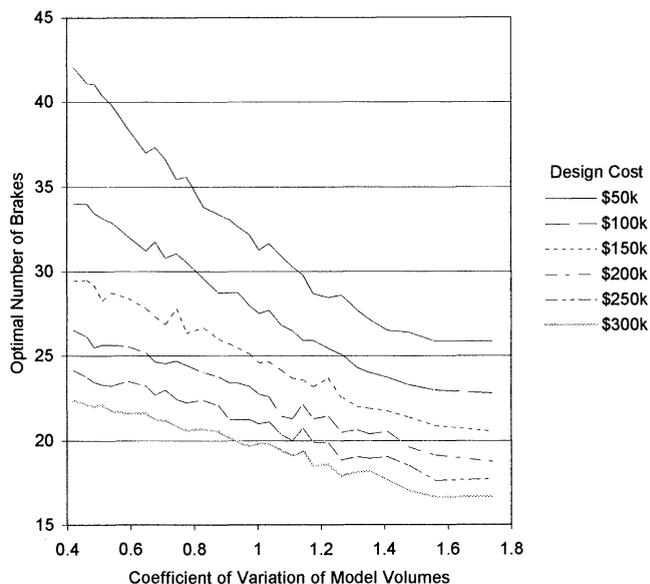
The formula for N_B^* is useful in evaluating data on the number of brakes offered by various auto companies with diverse product lines. Since each auto company offers a different range of models with varying weights and sales volumes, it is difficult to know from the number of brakes offered alone whether a particular company shares more or less than others since differences in the number of components could simply be due to differences in the model mix. However, the formula for N_B^* can be used to normalize the number of brakes offered comparing sharing levels. If we assumed that all firms have access to roughly the same design and production technology (i.e., K/c^F is the same for all companies), we would expect the number of front brakes offered for a given N to vary with $\sqrt{(W_{\max} - W_{\min})V}$. Assuming firms have access to different technologies (i.e., K/c^F is different for different companies), the relationship can be tested by controlling for individual firms, or for groups of firms with similar technologies.

Impact of Variation in Volume Across Models

Consider the impact of variability in volume across models. When volume is distributed unevenly, components may be developed opportunistically to take advantage of the "lumpiness" in volume. The products with higher-than-average volume are equipped with components that are precisely matched to these products' requirements, but the lower-volume products use components borrowed from the high-volume products. The intuition behind this approach suggests that as variability in volume across models increases, the optimal number of components decreases.

We explored the significance of this phenomenon by solving, via the shortest path algorithm, a series of cases in which the V_j are generated with Monte Carlo methods from a gamma distribution. The gamma distribution was used because it provides a good fit to the actual distribution of sales volumes in each company, since it is skewed and all draws are nonnegative. We set $N = 50$ and the mean μ of the gamma distribution equal to 200,000 units. We used six values of standard deviation σ chosen so that the coefficient of variation $c_v = \sigma/\mu$ ranged from 0.5 to 1.5, in increments of 0.2. For each value of σ , we generated demand for 100 test problems via Monte Carlo simu-

Figure 2 Results of Simulation Investigating the Effect of Variability in Model Volume on the Optimal Number of Brake Rotors. The Results Shown Are for a Mean Lifetime Model Volume of 200,000 Units



lation, for a total of 600 test problems. We solved each test problem to determine the optimal number of front brakes, for each of six values of design cost c^F , ranging from \$50,000 to \$300,000, in increments of \$50,000. (The values for volume, coefficient of variability, and design cost are in the range of those of industrial practice. We also performed this analysis with other sets of parameters with equivalent qualitative results.)

To examine the impact of increased demand variability on the optimal number of front brakes, we ordered all 600 test problems by increasing observed coefficient of variation of model volumes. To smooth the data, we then partitioned the set of test problems into consecutive subsets of twenty. We next plotted the average optimal number of front brakes for each subset against the corresponding average coefficient of variation (Figure 2). The figure shows that the optimal number of front brakes tends to decrease as variability in volume across the product line increases; this effect is significant.

4. Empirical Evidence on Brakes Sharing in the Auto Industry

In this section, we report on an empirical study of front brakes sharing practice based on data from three

American and three Japanese car companies over the 11 year period 1982–1992. Our goal was to examine how much variation exists in actual brakes sharing practice, and to identify factors that can explain this variation. Our work builds on a substantial body of academic research conducted on product development and manufacturing in the auto industry over this same time period. An excellent summary of this research is included in Cusumano and Nobeoka (1992).

Data

Our sample of companies includes Chrysler, General Motors (GM), Ford, Honda, Nissan, and Toyota. We examined all divisions of GM including Saturn, all divisions of Ford and Chrysler, Honda including its Acura division, Nissan including its Infiniti division, and Toyota including its Lexus division.

We obtained data on component sharing from ADP Hollander Inc., an independent automotive research company that sells databases containing information on interchangeable components to auto salvage yards. Hollander itself uses several data sources, including auto magazines, industry sources such as the Motor Vehicle Manufacturers Association, manufacturer surveys, physical tear down analyses of vehicles, and reports from client salvage yard owners about what components they have seen used on specific car models. For each company and model year, this data enables us to determine what front brake was used on each model in the product line, for models sold in the U.S. This data is only available for U.S. models, which limits our analysis. We explain in the next subsection how we have attempted to adjust for this limitation in our data set.

We also collected publicly available data on the weight, platform designation, and yearly sales volume of each model in our study. These data come from *Automotive News Yearly Data Book*, *Wards Automotive Year Book* and *Motor Business International*. In addition to collecting data from public sources, we had extensive discussions with several brakes design engineers and other auto industry employees, in order to understand the factors that impact front brakes decision making.

Variables

We used the following variables in our study. Each variable is defined for each company in each model year.

N_B : number of unique front brake rotors used by the manufacturer (dependent variable).

N_p : number of platforms (i.e., vehicles with different wheelbases) in the product line of the manufacturer.

R_w : range of weights of all models offered by the manufacturer.

V : estimated sales volume of all of manufacturer's models over their remaining lives.

c_v : coefficient of variation of model volumes.

$\sqrt{R_w V}$: a composite variable based on the range of weights and total remaining sales volume of all models in the product line of the manufacturer.

Y : a time variable with values ranging from 1 to 11 corresponding to the years 1982 to 1992.

N'_B : number of unique front brake rotors used by the manufacturer last year (lagged dependent variable).

X_{US} : a dummy variable set equal to one for U.S. companies and zero for Japanese companies.

Due to data restrictions, our primary data was limited to models that were sold in the U.S. For Ford, GM, and Chrysler, the product development organizations for models sold in the U.S. were separate from those for models sold in other markets, during 1982–1992. Therefore, this limitation posed no problem for these companies. For the Japanese companies in our study, some cars sold in the U.S. shared brakes with models sold in other markets. Since our data on parts sharing was limited to models sold in the U.S., we assumed that each Japanese model sold in the U.S. shared brakes with those models sold outside the U.S. that used the same platform. For each Japanese company, we expanded the number of models each year to include all such models. This adjustment is an approximation because (a) it excludes models sold outside the U.S. which shared a brake, but not a platform, with a model sold in the U.S., and (b) it includes models sold outside the U.S. market that shared a platform, but not a brake, with a model sold in the U.S.

The variables V and c_v are volume related. Since the life cycle volume of any model is spread over several years, we adjusted the total sales volume for each

company each year (which is public data) as follows to estimate total remaining life cycle volume. Let L denote the average length of a car's life cycle before a major model change. Clark and Fujimoto (1991) reported that the average major model change frequency for Japanese and American manufacturers was 4.6 years and 8.1 years respectively, during the period 1982–1987. Since product life cycles for most cars have continued to decrease over time and our study covers the period 1982–1992, we assumed that the average length of life cycle for Japanese models was four years, and that the average length of life cycle for American models was seven years, during the period 1982–1992. For any company, let V_t denote the total sales volume for all models sold in year t . We estimate the remaining life cycle sales volume for all models sold in year t as follows:

$$V = \sum_{i=0}^{L-1} \left(\frac{L-i}{L} \right) V_{t+i}. \quad (4)$$

The above adjustment assumes, for example, that for the Japanese companies with an average model life cycle L of four years, three-fourths of the cars offered in any year will be continued into the next year, half will be continued for the next two years, and one-fourth will be continued for the next three years. For the Japanese companies in our study, we did not have access to model volumes for those models sold outside the U.S. that shared a platform with a model sold in the U.S. for all years in our study. We therefore used the following procedure to estimate these volumes in the aggregate. For each Japanese company, we subtracted U.S. sales from world wide sales (production figures from *Wards Automotive Year Book* provided an accurate proxy for the latter) to obtain non-U.S. sales each year. We then estimated the portion of the non-U.S. sales for each company that was attributable to models that shared a platform with a model sold on the U.S. market, each year. We did this by multiplying total non-U.S. sales each year by a factor $p < 1$, where p was determined from actual model level sales data for 1987, which we treated as a representative year for the study.

For each company and model year, the coefficient of variation of model volumes, c_V , was calculated as the

ratio of the standard deviation of volumes of models offered in that year and the mean volume per model in that year. Although it would be more correct to consider the mean *remaining* life cycle volume of models offered each year and the standard deviation of *remaining* life cycle volumes, we were unable to do so due to data limitations. Since our data on the non-U.S. sales volumes for Japanese companies was estimated at the company level and not the model level, we estimated c_V using data for models sold on the U.S. market only.

The variables N'_b and Y were included as control variables. We found that a front brake introduced in any model year was typically used for a period of several years. Our data on the usage of each front brake over time indicates that part of the reason for the greater variety in braking components in the later years of our study was the effect of accumulation of brakes over time: Companies would often keep old brakes in circulation even after introducing new ones. Although the average age of a front brake was smaller for the Japanese companies in our study than for the U.S. companies (1.3 years for the Japanese companies vs. 3.5 years for the American companies), our data showed that the tendency to accumulate brakes over time was common to companies in the U.S. as well as in Japan. To control for this tendency, we introduced the variable N'_b . In addition, we introduced the variable Y in order to control for changes in the companies' operating environments over time that may have resulted in "across-the board" changes in company strategies toward brakes variety over time, above and beyond the impact of accumulation of existing brakes.

Data Analysis

Table 1 presents some descriptive statistics obtained by aggregating data for each company over the years 1982 through 1992. Tables 2 and 3 contain correlations and summary statistics for the variables defined in the previous subsection. The top row of Table 1 reports the number of distinct front brakes used in cars sold in the United States during 1982–1992, by company. Row two reports the average age of front brakes used in this period, by company. Rows three and four report the number of distinct models and the number of distinct platforms used by each company in this time

Table 1 Aggregate Data for the Period 1982–1992

	GM	Chrysler	Ford	Honda	Nissan	Toyota
No. of front brake rotors, N_B	51	27	28	27	33	42
Ave. design age of rotor (years)	3.55	3.96	3.09	1.19	1.19	1.44
No. of models offered 1982–1992	58	38	28	7	17	16
No. of platforms used 1982–1992	37	28	21	17	14	12
Ave. no. of models per rotor	2.61	2.00	2.03	1.04	1.02	0.86
Ave. no. of platforms per rotor	1.00	1.44	1.07	1.04	0.95	0.84
Std. dev. of model weights, (kg)	236	191	281	143	208	195
Range of model weights, (kg)	1252	849	1087	648	736	812
Ave. st. dev. of weights of models using the same rotor (kg)	69	99	93	33	39	39
Ave. range of weights of models using the same rotor (kg)	228	333	293	84	91	97

Table 2 Correlations (Pearson) Between Variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1 N_B	—												
2 $\sqrt{R_w V}$	0.72	—											
3 c_V	0.18	0.12	—										
4 X_{US}	0.43	0.56	-0.27	—									
5 N_P	0.85	0.73	0.20	0.67	—								
6 Y	0.53	0.09	0.52	0.00	0.41	—							
7 N'_B	0.92	0.71	0.16	0.42	0.84	0.53	—						
8 R_w	0.74	0.88	0.12	0.66	0.78	0.33	0.74	—					
9 V	0.62	0.96	0.11	0.46	0.64	-0.06	0.61	0.71	—				
10 Chrysler	-0.17	-0.33	-0.28	0.45	0.13	0.00	-0.16	-0.11	-0.38	—			
11 Ford	0.05	0.28	-0.22	0.45	-0.02	0.00	0.03	0.42	0.15	-0.20	—		
12 Honda	-0.35	-0.45	0.32	-0.45	-0.38	0.00	-0.35	-0.50	-0.38	-0.20	-0.20	—	
13 Nissan	-0.17	-0.27	0.12	-0.45	-0.26	0.00	-0.17	-0.22	-0.28	-0.20	-0.20	-0.20	—
14 Toyota	-0.06	-0.02	-0.08	-0.45	-0.26	0.00	-0.05	-0.16	0.03	-0.20	-0.20	-0.20	-0.20

period. Since brake performance is very dependent on weight, we also calculated the range of weights and standard deviation of weights of all models offered by each company in the period 1982–1992. Rows seven and eight report these measures, both of which are smaller for the Japanese companies in our data set. We also examined the extent to which brakes were shared across models with differing weights. For each company, we computed the standard deviation and range of weights of all cars that used each unique front brake offered in the period 1982–1992. For each company, these numbers were averaged over all front brakes used in this period to obtain the average standard deviation and weight range of models served by each

unique brake (rows seven and eight). We found that both the average standard deviation and the average range of weights of cars that shared a front brake were significantly higher for Ford, GM, and Chrysler than for each of the three Japanese companies.

Clearly there *is* variation in the front brakes sharing practices of different firms. In an attempt to explain these differences, we tested several hypotheses that emerged from our theoretical analyses presented in §3, and the data analysis presented above.

Hypotheses

The following hypotheses were tested using data consisting of an observation for each company in each

Table 3 Summary Statistics

	Mean	Median	S.D.	Min	Max
N_B	10.05	9.00	4.77	4	25
$\sqrt{R_w V} (\times 10^{-4})$	6.88	5.93	2.76	2.09	12.81
c_V	0.99	0.95	0.28	0.47	1.88
N_P	9.95	9.00	3.89	3	21
N'_B	9.27	8.00	4.49	3	25
R_w (kg)	757	725	225	194	1243
$V (\times 10^{-6})$	6.49	5.11	3.73	2.27	16.8

model year beyond the first, a total of 60 observations (6 companies and 10 model years).

HYPOTHESIS H1. *Front brakes variety is increasing in $\sqrt{R_w V}$.*

We would expect front brakes variety to be increasing in R_w because the suitability of a brake for a vehicle is directly related to weight: heavier cars need bigger brakes, while smaller brakes will suffice for lighter cars. As model volumes increase, we expect to see more brakes because the fixed design cost is spread across more units. The specific functional form of the variable in Hypothesis H1 emerges from the theoretical model presented in §3.

HYPOTHESIS H2. *Front brakes variety is a decreasing function of the variability in model volumes.*

This hypothesis is consistent with the findings reported in §3. As variability in model demands increases, volumes for some models will fall below the threshold level needed to justify a unique brake. This effect would cause the number of front brakes to be decreasing in volume variability. We will measure variability in model volumes by coefficient of variation, c_V , in order to adjust for differences in the mean volume of models offered by different companies.

HYPOTHESIS H3. *U.S. firms exhibit a greater amount of front brakes sharing than do the Japanese firms in our study.*

In a multiyear study of the auto industry, Clark and Fujimoto (1991) reported that the Japanese companies in their study were more efficient in product development than were their American counterparts, in terms of both engineering lead time and total engineering

hours expended. Thus these companies could probably offer higher component variety for the same effort and time expended. This is consistent with expression (3) for N_B^* in §3: More efficient product development means small c^f and relatively greater N_B^* . In fact, Clark and Fujimoto found that Japanese cars used a higher percentage of unique components than did American cars. Their research suggests that to support this strategy, the Japanese companies followed the policy of subcontracting much of their component design function to component suppliers, while maintaining enough flexibility in their auto assembly plants to support high levels of component as well as product variety. Clark and Fujimoto also reported that Japanese car development projects in the 1980s were headed by a "shusa" or heavyweight project manager, who had complete authority over the project. This type of strong project leadership may have resulted in less communication, and therefore less components sharing, between development projects. Finally, Clark and Fujimoto show that design quality is higher, on average, for the Japanese firms than the U.S. firms over the period of the study. One element of design quality is "product integrity" (Clark and Fujimoto 1990), which is enhanced by unique components tuned to the needs of unique products (Ulrich and Ellison 1998). Based on this research, we would expect brake rotor sharing to be lower in the Japanese firms than in the U.S. firms.

HYPOTHESIS H4. *Front brakes variety is an increasing function of product line variety.*

If a firm adopts no component sharing, then clearly component variety must increase with product line

variety. However, in our analytical model, brake rotor variety is independent of the number of models in the product line (for a given product line volume and range of vehicle weights and assuming that there are relatively many models in the product line). Two organizational factors may cause actual practice to deviate from this model. First, as noted in the discussion of Hypothesis H3, there has been a trend in the past decade to employ autonomous project teams with "heavyweight" project managers. As individual teams gain autonomy we expect to see component variety to be driven by end product variety. Second, there may be an organizational tendency to "start from scratch" in engineering design, perhaps another incarnation of the Not-Invented-Here (NIH) syndrome. In the absence of perfectly rational, centrally coordinated component sharing practice, we would expect component variety to be increasing in product line variety.

Regression Analysis

Since our data is in the form of a panel comprised of six groups (companies) over 11 years, we first checked for violations of the standard OLS assumptions associated with this special data structure. A common problem in panel data is grouped heteroskedasticity, which occurs if the error variance differs across groups. Using the Breusch-Pagan test (Breusch and Pagan 1979), we discovered that our data does exhibit grouped heteroskedasticity. To correct for this problem, we used estimated generalized least squares (EGLS) rather than ordinary least squares, and included a correction for grouped heteroskedasticity in the EGLS computation.

Since a panel data set is comprised of several time series (one for each company) pooled together, another potential problem is serial correlation between error variances within each of these time series. Since we included a lagged dependent variable as an explanatory variable, we could not use the standard Durbin-Watson test to check for serial correlation. We therefore used the McLeod-Hunter test, recommended by Kennedy (1992) for this type of data set. We found no serial correlation. This is not surprising, given that we include a lagged variable as a regressor.

Next we determined the model specification. Even though the companies in our study are quite different

in terms of number of models and number of brakes, we hypothesized that we could pool the data from all six companies and include a dummy variable to capture U.S.-Japan differences. This is because the companies are all major mainstream car manufacturers (we did not include any specialty car or high-end-only producers), and are fairly similar to one another in terms of market segments served and geographical regions served.

The error structure in a pooled data set of this kind may require an error-components formulation, if the error term consists of a company-specific component, a time-specific component, and a truly random component. However, we determined through a Hausman test that an error-components formulation was not necessary (Hausman 1978).

We then performed a series of likelihood ratio tests to confirm our hypothesis that using a pooled data set along with a dummy variable to capture regional differences between the U.S. and Japan was appropriate. These tests essentially compare the significances of regional groups of individual company dummy variables to that of a single dummy variable distinguishing between the two regions, U.S. and Japan. In each case, individual company dummy variables were not justified.

We also hypothesized that any differences in factors affecting brakes sharing between the U.S. and Japanese firms in our pooled data set were best captured by a cell-mean corrected model (Hsiao 1988), which would allow for a different intercept but constant slope coefficients for the two regions. This is reasonable because there is little reason to expect that the explanatory factors would affect brakes variety differently in the two regions, as all the firms in both regions are mainstream manufacturers, use similar braking system technologies, and serve similar market segments and geographic regions. We constructed a fully interacted regression model in which the U.S. dummy variable was interacted with each of the remaining variables. Based on a likelihood ratio test using this and the previous regression, we found that the coefficients on the interaction terms were not jointly significant, indicating that a cell-mean corrected model was appropriate.

Table 4 Results of the Regression Analysis for Primary Hypothesis Tests

	R1	R2	R3	R4	R5	R6	R7	R8	R9
Constant	0.78* (1.66)	0.54 (0.99)	-0.31 (-0.55)	-0.86 (-1.32)	0.25 (0.32)	-0.05 (-0.07)	0.61 (0.89)	-0.10 (-0.12)	0.35 (0.42)
N_b	0.99*** (20.11)	0.96*** (16.07)	0.70*** (6.98)	0.61*** (5.83)	0.50*** (4.25)	0.37*** (2.94)	0.40*** (3.18)	0.48*** (3.94)	0.39*** (3.07)
Y		0.08 (1.00)	0.12 (1.51)	0.19** (2.30)	0.35*** (3.15)	0.39*** (3.70)	0.43*** (3.69)	0.27*** (2.58)	0.43*** (3.45)
N_p			0.33*** (3.13)	0.25** (2.22)	0.33*** (2.86)	0.52*** (3.61)	0.50*** (3.43)	0.52*** (3.44)	0.51*** (3.48)
$\sqrt{R_w V} (\times 10^6)$				23.3* (1.76)	26.3** (2.02)	37.7*** (2.81)			
c_v					-2.00** (-2.23)	-2.97*** (-3.00)	-3.03*** (-3.07)	-2.43** (-2.41)	-3.02*** (-3.02)
X_{US}						-1.35** (-1.98)	-1.00 (-1.48)	-1.26 (-1.62)	-1.13 (-1.52)
R_w								0.0024 (1.43)	0.0006 (0.30)
$V (\times 10^6)$							0.24*** (2.60)		0.23** (2.27)
N	60	60	60	60	60	60	60	60	60
Pseudo R^2 (see note)	0.838	0.841	0.865	0.873	0.875	0.886	0.882	0.873	0.883

*** = $p \leq 0.01$, ** = $p \leq 0.05$, * = $p \leq 0.10$, two-tailed test.

Note: The dependent variable is number of brakes, N_b . All results were computed using EGLS with a correction for grouped heteroskedasticity. T -statistics are shown in parenthesis. A conventional adjusted R^2 calculation is suspect and no longer a measure of goodness-of-fit when used with the EGLS procedure (Greene 1990). As a result, we compute the square of the simple correlation between the actual and predicted values of the dependent variable, which is used as a proxy in practice. We report this figure as a "pseudo R^2 ."

Although a subset of the independent variables exhibit some multicollinearity, the regression diagnostics recommended by Kennedy (1992) indicate that multicollinearity is not likely to bias the results.

Table 4 reports the results of our hypothesis tests in which we measure the impact of the explanatory variables on the number of unique front brakes observed in practice. In regressions R1 through R3 we add control variables one at a time (N_p , which is used to test H4, can also be viewed as a type of control variable). In regressions R4 through R6, we added the explanatory variables to test H1 through H3, one at a time. The coefficients of the variables associated with H1, H2, H3, and H4 are all significant and in the expected direction ($p \leq 0.05$ for all variables). R7, R8, and R9 test alternative functional forms for the variables V and R_w . V is substituted for $\sqrt{R_w V}$ in R7, R_w is substituted for $\sqrt{R_w V}$ in R8, and V and R_w are included as separate terms in R9. The coefficient of V

remains significant and of the expected sign throughout, but the coefficient of R_w is not significant (although the sign is in the expected direction).

Key Findings

There is support for the hypothesis that the number of brake rotors increases with $\sqrt{R_w V}$ (H1). This result supports the view that sharing is practiced, in the industry as a whole, according to an economic logic consistent with our analytical model. However, we note that the specific functional form $\sqrt{R_w V}$ should probably not be interpreted too strongly. V and R_w are highly correlated in our sample, and volume alone is nearly as good in explaining the variance in the data. There is support for the hypothesis that the number of brake rotors decreases as the variation in volume across different models increases (H2). This is consistent with the theory that, for a given total product volume, "lumpiness" in the distribution of this vol-

ume gives rise to the possibility of opportunistically assigning unique rotors to the models with high volumes, while sharing components across the models with low volumes. These two findings are important in that they point to an underlying technical and economic logic for differences in the component sharing practices among Japanese and U.S. firms and among firms within each region. The variation in component sharing practice can be attributed to a large extent to differences in the nature of the product lines offered by the firms.

Our results also indicate that, other factors being equal, Japanese companies share less than the U.S. companies (H3). This result from the regression analysis is further supported by the simple observation of the much lower design age of the Japanese brake rotors (Table 1) compared with the U.S. rotors. There are at least three possible theories that are consistent with this result. First, the fixed costs of creating a new rotor may be lower for these firms, giving rise to a higher optimal number of brakes. Second, the Japanese firms, on average, invoked heavyweight project organizations for product development more frequently than the U.S. firms over the period of the study, and therefore the Japanese product development organizations may lack the cross-project coordination mechanisms present in the U.S. firms. Third, the design quality of the Japanese vehicles was higher, on average, than that of the U.S. firms over the same period. Part of design quality may be "product integrity," which is strengthened by optimization of unique components for a single product application.

We observe a positive relationship between the number of different products, as indicated by the number of platforms, and the number of different front brake rotors. This result supports Hypothesis 4—that the number of different components is driven by the number of different products. On average over the entire data set and controlling for the other factors, for every two additional platforms there is one additional rotor. As we note in the presentation of Hypothesis 4, there are several possible theories for why this relationship exists. There may be an organizational tendency to "start from scratch" in designing a new product, perhaps because of the costs of finding and

testing an existing component. There has also been an overall trend in industrial practice toward more autonomous project teams. Such autonomy carries with it the difficulty of achieving the economies of component sharing.

5. Concluding Remarks

We have developed an analytic model of component sharing and shown through empirical testing that this model explains much of the variation in sharing practice for automotive braking systems. Here we discuss the degree to which we believe these results can be generalized, we highlight implications for industrial practice, and we outline directions for future research.

Generalizing the Results

In the introduction to the paper, we argued that components could be usefully divided into two categories (A and B), with Category A components significantly influencing product quality, and Category B components nearly invisible to the customer. We focused the paper on Category B components, and then further focused on front brake rotors in the automobile industry. Here we consider to what extent the insights from the paper apply to other Category B components, and then to what extent they apply to Category A components.

The front brakes sharing problem exhibits the following properties:

- The products over which a component is to be shared employ the same type of component (e.g., the automobiles all employ brake rotors).
- Products can be ordered by the performance requirement of a component to be shared (e.g., auto models can be ordered by minimum acceptable rotor diameter).
- By the definition of Category B components, components are downward compatible with no substantial effect on overall product quality (e.g., a brake rotor used on a large vehicle can also be used on a smaller vehicle with no substantial degradation in vehicle performance).
- The cost of producing a component is an increasing function of its performance (e.g., larger rotors cost more to produce than smaller rotors).

- The costs of producing components exhibit economies of scale (e.g., producing 400,000 rotors is less than twice as costly as producing 200,000 rotors).

We believe that many other categories of products and components share these properties. For example, computers can be ordered by the minimum required hard drive capacity, higher capacity hard drives can be used in computers requiring less capacity, the cost of producing a higher capacity drive is greater than that of producing a lower capacity drive, and hard drive production exhibits economies of scale. Similar arguments could be made for many other product categories and components, including apparel and fabric components; power tools and motor components; food products and sweetener components; and consumer audio electronics and amplifier components. In situations in which these properties hold, we would expect the basic insights from the analytical model to be valid. The number of components to be used for a given number of types of products will be increasing in the range of the performance requirements; increasing in the overall production volume of the set of products; and decreasing in the magnitude of the economies of scale. We would also expect fewer components (more sharing) as the variability of volume across different products increases. None of these results is unique to the automotive domain, nor to braking systems.

In focusing on Category B components, we ignore those quality implications of component sharing that cannot be modeled as a "unit cost" (as can the cost of excess weight in automobiles). As a result, when applied to Category A components, the insights from the brake example may lead to cost minimization, but will not necessarily lead to profit maximization. There has been some early research on integrating revenue and cost models. Ramdas and Sawhney (1998) empirically estimate the revenue and cost impact of component sharing decisions and model optimal product line management for holistic products. In research that is closely analogous to the component sharing problem, de Groote (1994) and Krishnan et al. (1997) characterize product quality by a single attribute and assume that customers experience decreasing utility for a product as it deviates from their "ideal point."

One of the challenges in extending research in this area is developing richer models of the relationship between component sharing and product quality, especially for product categories in which holistic customer requirements are important.

Managerial Issues and Implications for Practice

While the primary focus of this research is to describe and explain industrial practice, several managerial issues and implications for practice arise from the work.

First, we believe that the categorization of components into those with a direct impact on product quality (Category A) and those with a limited impact on product quality (Category B) is worth applying in practice. We observed a similar categorization at Toyota (into "functional" and "aesthetic" components) and feel that dividing components into these categories helps guide the component sharing effort. There are likely to be many opportunities for improved sharing practice even within Category B components, without having to wrestle with the question of how component sharing influences product quality.

Second, once a component category has been identified as a candidate for sharing, we believe that an analysis like the shortest-path optimization we have described can be applied in practice. It is generally not possible to model the sharing decision with perfect accuracy, especially given the limitations of most cost data, but basic insights can be derived about how many components to use and which products should have product-specific components. In our interviews with automobile industry engineers and managers, we saw no such analysis, although some of the basic trade-offs are well understood at a qualitative level. The analysis could be applied, with very little modification, to many types of Category B components, including bearings, fasteners, electric motors, switches, door latches, and wiring harnesses.

Third, the challenge of component sharing is increased as the decision is viewed dynamically. In most industrial situations, there already exists a portfolio of products and the managerial problem is to decide which components to re-use, which components to replace, and which new components to develop. This

problem is complex and deserves further research attention. However, one approach to this problem is to perform the static analysis we propose, but for a hypothetical family of products based on plans for the future. Then, once the optimal set of components is identified, the firm could develop the subset of components that are needed for products under current development, even if some of these components will be designed to accommodate other products that will not be developed for several years.

Fourth, the decision making described in this paper is from the perspective of an omniscient central planner. However, in practice, product development projects are frequently decentralized. A managerial challenge is to coordinate disparate efforts in a way that component development efforts can be shared. We have seen at least three coordination mechanisms used in practice: Some firms simply assert a "menu" of possible components from which a project team can choose; some firms attempt to institute market-like mechanisms by using cost accounting schemes that reflect the true costs of shared versus unique components; and some firms attempt to inculcate development teams with strong cultural norms about the importance of component sharing and interproject coordination.

Finally, a striking observation from our empirical investigation is the accumulation of brake rotors over time. We have also observed this tendency for other automobile components (Fonte 1994) and suspect it occurs in other industries. We see a need for occasional "spring cleaning," in which component needs are consolidated and redundant components eliminated. While the economic benefit of such rationalization is not likely to be as great as if the excess components were never developed in the first place, removing a component from use may reduce unit variable costs because of increased product volume, and may reduce the system costs of inventory, quality management, and vendor management.

Future Work

Several opportunities for future research are implied by the preceding discussion. Here we identify some of these opportunities explicitly.

- Models linking component sharing to product quality need to be developed for Category A components.

- An understanding needs to be developed of how organizational structure (e.g., heavyweight vs. lightweight project organizations) and governance mechanisms influence component sharing. This understanding should then be used to develop mechanisms to enhance coordination across projects.

- Assuming that the accumulation of components over time is harmful, why does it happen in the first place, and how can it be prevented?

- What types of decision support tools can support managerial decision making? To what extent must they be idiosyncratic to a particular type of component? Although we have developed one such tool (Ramdas 1995) that accommodates compatibility constraints among sets of components used in a system, the development and implementation of other tools may be useful.⁷

⁷ We are grateful to members of the Design Staff and the Brake and Bearings Systems Center at General Motors and the NAAO Complexity Office at Ford Motor Company. We are grateful to ADP Hollander Inc. for providing data. We are thankful for useful conversations with auto industry analysts at Maritz Market Research Inc. and *Automotive News*. We are grateful to Jung Lee, Anand Paul, and Taylor Randall for assistance with data collection and analysis, and to Mamta Murthi, Shubham Chaudhuri, and John Penrod who provided extremely valuable technical assistance. We are also thankful to Luk Van Wassenhove and three anonymous reviewers for their significant contributions to the paper.

Appendix

PROPOSITION. *There is an optimal solution in which each car j uses the smallest introduced rotor with diameter not less than d_j .*

PROOF. Suppose there is an optimal solution which violates this property. Then there must be a car j that uses rotor k when there is an introduced rotor i with $j \leq i < k$. We show how to create a new optimal solution in which either car j uses rotor i or all cars assigned to rotor i are reassigned to rotor k and rotor i is no longer introduced. Repeated application of this argument will produce a solution with the required property.

Let \bar{V}_i and \bar{V}_k be the total sales volumes of all cars that use rotors i and k respectively in the given solution. If $c_k(\bar{V}_k) - c_k(\bar{V}_k - V_j) \geq c_i(\bar{V}_i + V_j) - c_i(\bar{V}_i)$, we can assign car j to rotor i without increasing cost. Next consider the case in which

$$c_k(\bar{V}_k) - c_k(\bar{V}_k - V_j) \leq c_i(\bar{V}_i + V_j) - c_i(\bar{V}_i). \quad (A1)$$

By the concavity of c_i , we have

$$c_i(\bar{V}_i) \geq \left(\frac{V_j}{V_j + \bar{V}_i} \right) c_i(0) + \left(\frac{\bar{V}_i}{V_j + \bar{V}_i} \right) c_i(\bar{V}_i + V_j), \quad (A2)$$

which by algebraic manipulation yields

$$\frac{c_i(\bar{V}_i) - c_i(0)}{\bar{V}_i} \geq \frac{c_i(\bar{V}_i + V_j) - c_i(\bar{V}_i)}{V_j}. \quad (A3)$$

Similar logic applied to c_k shows that

$$\frac{c_k(\bar{V}_k + \bar{V}_i) - c_k(\bar{V}_k)}{\bar{V}_i} \leq \frac{c_k(\bar{V}_k) - c_k(\bar{V}_k - V_j)}{V_j}. \quad (A4)$$

From inequalities (A1), (A3), and (A4), we have

$$\begin{aligned} \frac{c_k(\bar{V}_k + \bar{V}_i) - c_k(\bar{V}_k)}{\bar{V}_i} &\leq \frac{c_k(\bar{V}_k) - c_k(\bar{V}_k - V_j)}{V_j} \\ &\leq \frac{c_i(\bar{V}_i + V_j) - c_i(\bar{V}_i)}{V_j} \\ &\leq \frac{c_i(\bar{V}_i) - c_i(0)}{\bar{V}_i}, \end{aligned} \quad (A5)$$

which establishes that

$$c_i(\bar{V}_i) - c_i(0) \geq c_k(\bar{V}_k + \bar{V}_i) - c_k(\bar{V}_k). \quad (A6)$$

By (A6), we can assign all cars using rotor i to rotor k and drop rotor i without increasing cost.

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